Renewable and Sustainable Energy Reviews 33 (2014) 141–153

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review of soft computing methods for harmonics elimination PWM for inverters in renewable energy conversion systems

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ARTICLE INFO

Article history:
Received 12 March 2013
Accepted 31 January 2014
Available online 25 February 2014

Keywords:
Renewable energy
Inverter
Harmonic elimination pulse width modulation
Soft computing

ABSTRACT

For a renewable energy (RE) system, an inverter is normally required to condition the dc power to ac, so that it could be connected to the electrical grid. At the heart of the inverter is the modulation strategy that synthesized the ac waveform by chopping the dc voltage using power electronics switches. Among the numerous modulation techniques, the harmonics elimination PWM (HEPWM) is preferable due to its superior harmonics profile; the elimination of low order harmonics results in reduced switching losses, hence improved inverter efficiency. However, the non-linear and transcendental nature of the HEPWM equations poses a challenge for the conventional computational methods (mostly calculus-based). With the advent of low cost and powerful computers, the soft computing (SC) approach seems to be a better approach and well suited to handle the complexity of the HEPWM problem. This review paper attempts to summarize the operation of the nine SC methods, as well as highlighting their advantages and limitations. Furthermore, the work also presents a critical evaluation on the performance of the three prominent SC techniques, namely, the Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Differential Evolution (DE). It is envisaged that the information gathered in this single reference will be useful for researchers, designers and practitioners that utilize HEPWM to design energy conversion system.

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http://dx.doi.org/10.1016/j.rser.2014.01.080
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1. Introduction

Concerns over the global warming due to greenhouse gases and the increasing scarcity of fossil fuels have been the motivating factors to the rapid progress in renewable energy (RE) research [1,2]. These alternative sources, particularly solar, wind, biomass, tidal and ocean thermal are more sustainable due to their natural abundance and environmental friendly in nature [3,4]. Despite higher initial investment cost, quite a significant number of countries, companies and organizations have embarked on RE-based power generation projects for commercial purposes. This can be attributed to the attractive long-term economic benefits that can be gained in various ways: almost zero fuel cost, lower maintenance (fuel and labor) and reduced penalties on CO_2 emissions. Moreover in some countries, financial incentives such as feed-in-tariff (FIT) schemes, initial subsidies and tax breaks are designed to accelerate the growth of the industry even further [5,6].

It is envisaged that in a foreseeable future, RE can be as competitive as the traditional fossil fuel electricity; in fact, in certain parts of the world, especially in places where the cost of fuel is high (due to location, transportation etc.), RE electricity has already reached the point of grid-parity [7].

In RE power generation (both for stand-alone and grid-connected), some kind of energy conversion process has to take place. This is because the output voltage of RE sources is captured in dc form, while the electrical transmission system and load are based on ac [8,9]. In these circumstances, an inverter system is required [10–12]. The main purpose of the inverter is to condition the dc voltage to ac, i.e. to construct an ac sinusoidal waveform from a dc source by chopping the latter using power electronics switches [11,13]. With the rapid growth of large scale PV power system (solar farms), inverters are connected to the electrical grid in the MW range [14]. Similarly, power conditioners for wind generation systems utilize power electronics converters which include inversion process [15]. Furthermore, a large number of appliances, for example motors [16], electronic goods and lightings are ac-based [17]; thus the inverter acts as a link between the generator to the loads and consumers [18]. Inverter is also widely found in the back-up or hybrid RE systems [19]; a good example would be the wind–solar-battery installations that are becoming more popular, particularly in remote localities or islands [18,20]. Another important application of inverters is the energy savings for heating and cooling systems. Their integration with the variable speed drive is crucial in reducing the energy consumption of cooling compressors [16]. In addition, inverters are also used in the voltage regulation and dynamic stability control of the electrical systems [20,21]. Judging by the rate they are being introduced to the energy industry, inverters are seen as indispensible equipment of the future.

Despite its growing importance, one of the major concerns of the inverter is the presence of significant amount of unwanted harmonics in its output voltage [22–24]. Harmonics are known to exhibit several detrimental effects on electrical and mechanical components: (1) it increases the switches losses of the semiconductor switches; this is particularly important for RE as it degrades the efficiency of the system [13], (2) it deteriorates the performance of the overall system [25]; for instance, it causes torque and speed ripple of induction motor and (3) it reduces the life time and reliability of the system due to vibration, torque pulsation and mechanical fatigue [26]. When connected to the electrical grid, the harmonics, particularly the lower order ones, are very undesirable as they cause a number of complicated problems at the distribution system [27]. To overcome these problems, tremendous amount of research have been carried out to control or mitigate the effects of harmonics in inverters [28,29]. The most crucial aspect is to devise an appropriate switching scheme for the power switches that can synthesize the ac waveform with the lowest total harmonic distortion (THD) [30]. In literature they are commonly known as the pulse-width modulation (PWM) strategies. Among the many available PWM techniques, the harmonics elimination pulse-width modulation (HEPWM) [31,32] has gained prominence due to its many benefits that shall be described later in this paper.

For HEPWM, a set of non-linear, transcendental simultaneous equations need to be solved to determine the switching angles that will force the elimination of selected harmonics. However, the convergence to solutions for these equations can be very difficult due to the interactions between the sine and cosine functions (of different frequencies). This problem is more severe as the number of angles to be eliminated increases. Furthermore, the trigonometric equations often result in multiple solutions that complicate the selection of the physically correct angles. Additionally, in certain cases, the computed angles do not have sufficient angular separation (i.e. the adjacent angles are too close to each other), making it almost impossible to create a pulse/notch in the output voltage waveform. Despite these difficulties, numerous computational methods to obtain the HEPWM solution sets have been proposed. The most popular approach is to employ the numerical techniques such as the Newton–Raphson method. It is a calculus-based approach that produces accurate solutions with good convergence, provided that the initial guesses for the angles are near the local minima [33]. However, if the initial values are not correctly chosen, the iteration cycles can be very large and in extreme cases, non-convergence can occur. This is particularly difficult for multilevel inverter with staircase waveform.

Recently, there are interests to solve engineering problem using optimization approach. One of its main tools is the soft computing

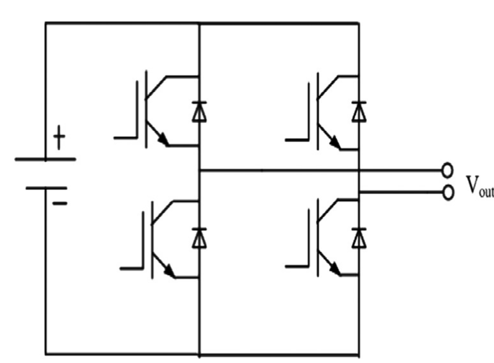

Fig. 1. A typical H-bridge VSI.

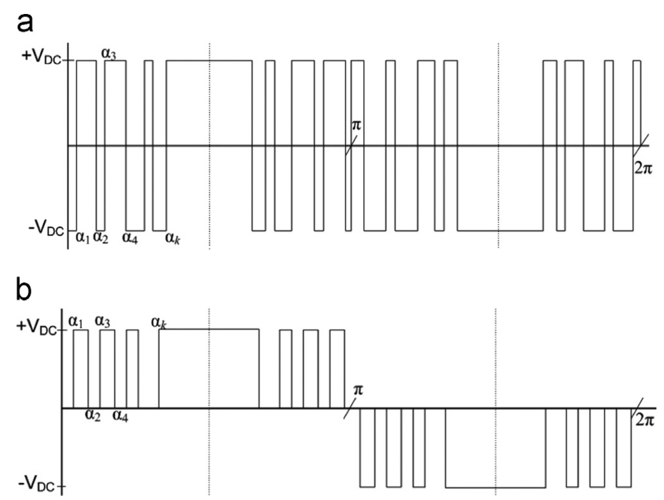

Fig. 2. Output voltage waveform of a VSI with (a) bipolar output voltage, and (b) unipolar output voltage.

(SC) techniques. The main strength of SC is its ability to handle non-linear mathematical problems in a non-conventional way. Adding to that, the availability of powerful and low-cost personal computers has made such complex computation feasible. In RE, SC has been applied to optimize the model for energy efficiency [34–36]. In the context of HEPWM, the main advantage of SC is the non-critical role of initial conditions because its operation is based on search or/and evolutionary approaches. Over the years, numerous works on SC for HEPWM are published. However, there appears to be an absence of a comprehensive review article of this subject (application of SC for HEPWM) in literature. Therefore, this paper is written with the objective of summarizing the work done in this field and to present it as a single reference. While doing so, it describes the operation of the nine HEPWM soft computing methods and highlights their advantages and limitations. Furthermore, a critical evaluation and discussion on the performance of the three prominent SC techniques, namely, the Genetic Algorithm (GA) [37], Particle Swarm Optimization (PSO) [38] and Differential Evolution (DE) [29] is carried out. It is envisaged that the information gathered in this paper is useful for researchers, designers and practitioners that utilize HEPWM for inverter designs. It also gives some indications on the future direction of research in this area.

2. Overview of inverter and modulation methods

2.1. Inverter topologies

Inverter is normally used for dc to ac power conversion purposes; in the context of RE, it converts dc voltage from the renewable sources to ac, so that the connection to the electrical grid can be made [39,40]. An inverter is classified as a current source (CSI) or voltage source inverter (VSI) [41]. The latter, being more widely used, will be the focus of this paper. Topologically, the VSI is categorized as a two-level inverter (generally termed as VSI) or a multilevel inverter (MVSI) [42]. The VSI can produce bipolar [29] or unipolar output waveforms [30]. Example of a typical H-bridge VSI is shown in Fig. 1, while Fig. 2 shows the bipolar and unipolar output voltage waveforms. In high and medium power applications (up to several MW), such as power conditioner for wind turbine, the semiconductor switch might be an IGBT, GTO and GCT. For low power equipment, for example an inverter for building integrated PV system, a lower rated IGBT or MOSFET is normally used.

2.2. HEPWM concept

The quality of a VSI output voltage is benchmarked by the total harmonic distortion (THD) [17] that it produced. The THD is defined as

$$\mathrm{THD} = \frac{\sqrt{\sum_{i=2}^{n}(V_i)^2}}{V_1} \tag{1}$$

In most cases, the THD is treated as the efficacy of the dc–ac energy conversion systems [43,44]. The recommended limit for THD is set by several organizations, for example [45].To reduce the THD, various modulation schemes have been introduced; these include single wave pulse-width PWM, multi-wave PWM, carrier-based PWM, sine-wave PWM (SPWM) and space vector PWM [46–48]. However, the harmonics elimination PWM (HEPWM) is preferred due to its superior harmonics performance. For the same switching frequency, the first harmonic incidence (location of harmonic in the frequency spectra) is approximately twice as that of the SPWM. As a result, switching loss is reduced. In addition, HEPWM is well suited for over-modulation, thus increasing the availability of the fundamental output for the same input voltage.

A generalized bipolar HEPWM waveform of a VSI is depicted in Fig. 2(a). The basic square wave is chopped such that the odd switching angles, i.e. α_1, α_3, α_5 etc. define the rising edge transitions, while the even switching angles α_2, α_4, α_6 etc. define the falling edge transitions. Since the waveform is quarter-wave symmetric, only odd harmonics exist (i.e. $B_n=0$); thus the nth harmonic is given by

$$A_n = -\frac{4}{n\pi}\left[1+2\sum_{i=1}^{k}(-1)^i \cos n\alpha_i\right] \tag{2}$$

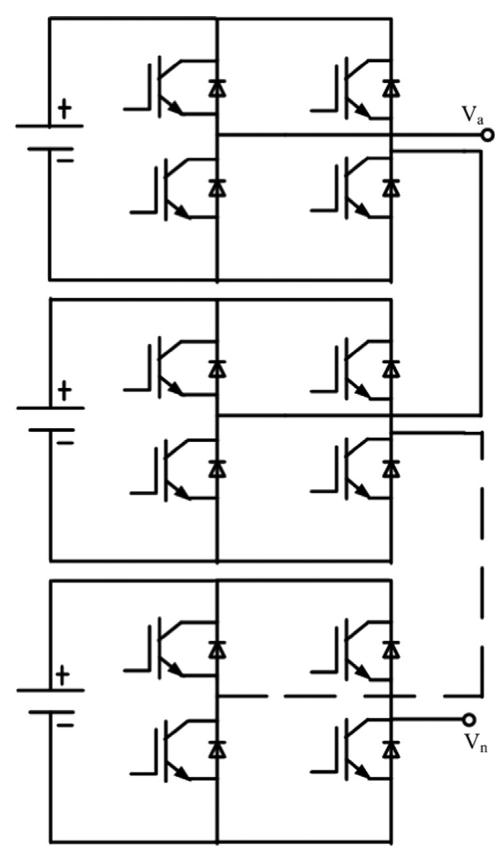

Fig. 3. Structure of a single phase cascaded MVSI.

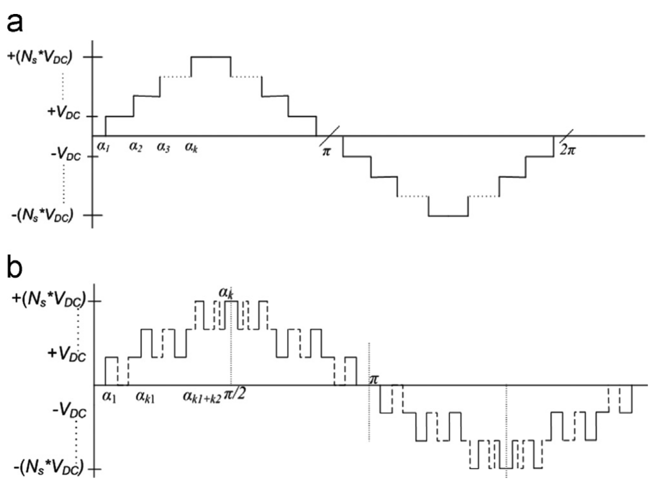

Fig. 4. The staircase output voltage of the MVSI (a) without chops within each level (type-*a*), (b) with chops within each level (type-*b*).

where α_i is the ith switching angle, n is the order of harmonics to be removed and k is the total number of switching angles. Note that Eq. (2) forms a set of simultaneous nonlinear transcendental equations, which has to be solved off-line. It has k variables (α_1 to α_k) and a set of solutions is obtainable by equating any $k-1$ harmonics to zero and assigning a value to the fundamental. The latter is achieved by setting the modulation index, M, to a particular value. By definition,

$$M = \frac{|V_1|}{V_{DC}} \tag{3}$$

where V_1 and V_{DC} are the amplitudes of the fundamental component and the dc input voltage source, respectively. Since M can exceed unity, it implies that over-modulation is allowed. For a three phase VSI, it is sufficient to eliminate the non-triplen harmonics only, as the triplens are absent in the line-to line waveform. Furthermore, for the waveform to be physically correct, the angles must be sequenced such that

$$\alpha_1 < \alpha_2 < \alpha_3 \ldots < \alpha_k < \frac{\pi}{2} \tag{4}$$

By expanding Eq. (2), the HEPWM objective functions which need to be solved can be derived as

$$f_h(\alpha) = -\frac{4}{n\pi}\left[1 + 2\sum_{i=1}^{k}(-1)^i \cos n\alpha_i\right] = \varepsilon_h,\ h = 1, 2, \ldots, k \tag{5}$$

where $f_h(\alpha)$ is the vector of the function to be minimized, while ε_h represents the amount of the error allowed for each harmonic. The latter is set to be near zero. It should be noted that for $h=1$, M should be summed with ε_h on the right hand side of the Eq. (5) in order to control the amplitude of the fundamental component of the output voltage. Moreover, the polarity of (-1) is positive and negative for the rising and falling edges of the output waveform, respectively.

2.3. Multilevel inverter (MVSI)

The MVSI is characterized by the number of voltage levels in a staircase (stepped) waveform that mimics the sinusoidal ac [49,50]. Despite its complexities, it is preferred due to its superior harmonics profile and its ability to produce high output voltage without a transformer [51–53]. The transformer-less inverter architecture is desirable in RE applications for several reasons: (1) it reduces the cost, weight and size of the system, (2) it results in less power losses and (3) lower rated switches can be utilized to generate high voltage output [52,54,55]. Various topologies are used; among the popular ones are the Point Clamp [56], Flying Capacitor [57] and Cascaded [58] MVSI. Fig. 3 shows a single phase cascaded MVSI. It comprises of several H-bridge inverter modules connected in series. The separate (independent) dc sources are a common configuration for RE application, particularly for PV power systems [59,60]. The overall output voltage is the vector sum of the output for each module. With regard to its HEPWM switching, two approaches are possible. First, the output voltage is constructed as a staircase waveform without any chop within the level, as illustrated in Fig. 4(a). For convenience, in this paper, it is referred to as the "type-*a*" switching. The second type is to introduce additional chops within each level, as shown in Fig. 4(b). This is referred as the "type-*b*" switching.

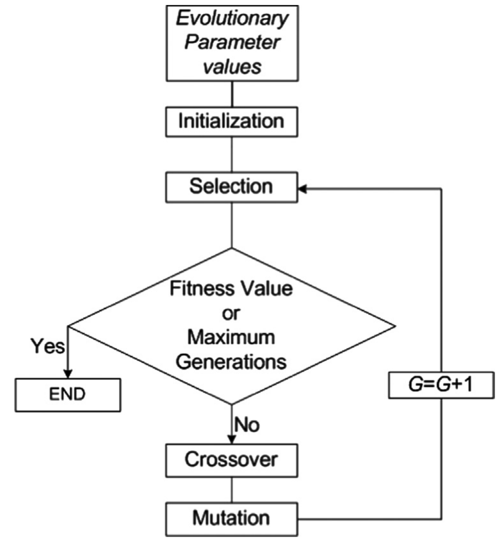

Fig. 5. Flow chart of GA.

For the type-*a* case, the HEPWM angles are computed only for the instants in which the transitions from one level to another occur, i.e. α_1, α_2,…,α_k, as depicted in Fig. 4(a).The advantages of this method is the ability to achieve high fundamental output voltage while maintaining low switching frequency. However, the number of harmonics that can be eliminated depends on the level of the output voltage; thus, to eliminate more harmonics, higher number of output voltage level is required. This constraint limits the number of harmonics that can be eliminated as the physical complexity of the circuit increases rapidly with the number of levels. The general objective function that allows the HEPWM to control the fundamental output voltage as well as its harmonics behavior can be written as

$$f_h(\alpha) = \sum_{i=1}^{k}(-1)^i V_i \cos n\alpha_i = \varepsilon_h \quad h = 1, 2, \ldots, k \tag{6}$$

where V_i is the magnitude of ith output voltage step. If N_S represents the total number of input sources, then the modulation index (M) is given as

$$M = \frac{\pi|V_1|}{4V_{DC}},\ 0.01 \le M \le N_S \tag{7}$$

It has to be noted that, to control the amplitude of the fundamental component, M needs to be added on the right hand side of the Eq. (6), as described earlier for VSI.

For the type-*b* HEPWM switching, the angles are not only computed for the transitions from one level to another, but also within each level itself. Hence, more harmonics can be eliminated without necessarily increasing the number of levels, as can be seen in Fig. 4(b). This is advantageous in two aspects: (1) the harmonics can be eliminated using lesser power electronics components and

Table 1
Summary of the GA related work in HEPWM.

Authors	Reference	Objectives of the work	Remarks
E. Butun, T. Erfidanand S. Urgun	[37]	Power factor improvement	GA is applied to improve the efficiency of systems containing inverters
M.S.A. Dahidah and M.V.C. Rao	[70]	Harmonics control of ac–ac converters	A combination of RCGA and DS is used to improve the harmonics profile of ac–ac converter systems
M.S.A. Dahidah, V.G. Agelidis and M.V. Rao	[72]	Harmonics control in utility power systems	Method of [70] is used to control harmonics in utility power systems
A.K. Al-Othman, et al.	[48]	Improvement of harmonics of utility power systems	A combination of RCGA and PS is applied to improve the harmonics behavior of the utility power systems
N. Tutkun	[46]	Efficiency improvement of grid connected system	A hybrid algorithm consisting of GA and NR is used to improve harmonics behavior of grid connected systems
S.R. Pulikanti, M.S.A. Dahidah and V.G. Agelidis	[74]	Zero/Neutral level current removal in NPC MVSI (type-*a*)	Method of [70] is used to remove the neutral point current from the NPC MVSI
K. El-Naggar and T.H. Abdelhamid	[67]	Harmonics removal in MVSI with reduced switches (type-*a*).	GA is used to enhance the harmonics profile of a newly introduced class of MVSI which contains less number of switching devices
M. Sarvi and M.R. Salimian	[75]	Harmonics mitigation in multilevel MVSI (type-*a*)	The objective of the work is to compare the performance of GA and PSO for HEPWM problem
S. Barkati, et al.	[33]	Harmonics mitigation using MVSI in induction motor systems(type-*a*)	RCGA and PSO are used to find the best initial solution which is then fine tuned by NR
M.S.A. Dahidah and V.G. Agelidis	[76]	Utilize maximum switching ability of the switches for MVSI (type-*b*)	Method of [70] is used to improve the harmonics behavior of MVSI for both equal and unequal voltage sources
V. Jegathesan and J. Jerome	[27]	Improvement of the efficiency of induction motor drive systems	GA and EP are applied individually to improve the harmonics behavior of induction motor systems

(2) the switching capability of the power semiconductor devices can be fully utilized. However, despite these benefits, the maximum achievable fundamental output voltage is less compared to the type-*a*.

Due to the complexity of the generalized equation for the type-*b* HEPWM objective function, a seven level case is considered. That equation is given by Eq. (8), but can be extended to any number of levels according to the needs.

$$f_h(\alpha)=\left(\sum_{i=1}^{k1}(-1)^{i-1}V_1\cos\alpha_i\right)+\left(\sum_{i=k1+1}^{k1+k2}(-1)^{i-(k1+1)}V_2\cos\alpha_i\right)+\left(\sum_{i=k1+k2+1}^{k}(-1)^{i-(k1+k2+1)}V_3\cos\alpha_i\right)=\varepsilon_h \quad (8)$$

In Eq. (8), V_1, V_2 and V_3 are the multipliers for the dc sources. The variable k represents the total number of pulses per quarter wave, with $k1$ and $k2$ as the number of chops in the first and second level, respectively. Clearly, the HEPWM equation for the type-*b* switching is much more complex and thus the methods to solve for its angles deserve more attention.

3. HEPWM angles computation using SC

Formerly, the calculus-based approaches are employed to solve the HEPWM simultaneous transcendental equation [31,33,61–63]. The most widely used is the Newton Raphson (NR) method [31]. However, NR requires good (suitable) initial angles guesses; they need to be close to the global minima in order to avoid being stuck at a local minimum. Over the years, various improved calculus-based schemes are suggested by researchers; among the more popular ones are the Walsh function [61,64], Sequential Homotopy [65] and Resultants Theory [66]. Generally they resulted in improved convergence and computational speed. Despite these facts, the issue of initial angles remains unresolved.

As the MVSI gains popularity, the complexity of the HEPWM problem increases rapidly due to the complexity of the multilevel structure and the constraint placed on the sequencing of the angles within the level. Consequently, the guess for "suitable" initial conditions becomes more complicated. This is particularly acute for the type-*b* MVSI. Under these circumstances, the calculus based method begins to show its inadequacy in providing consistently converging and reliable solutions. In order to overcome these deficiencies, the soft computing (SC) approaches are introduced [51,67,68]. In contrast to calculus method, SC converts the problem to an optimization task and solves it using the evolutionary or search mechanism [36]. It does not necessarily require a good initial guess and is less prone to get trapped at a local minimum [37]; consequently, its convergence and success rate are superior. Furthermore, due to its diversity, it increases the chance to obtain more than one feasible solution sets for the HEPWM angles.

The literature on SC for HEPWM is scattered in various journals: computing, electronics/electrical, mathematics, energy etc. To facilitate the readers in going through the related work, a systematic categorization of the techniques is offered in this paper.

3.1. Genetic Algorithm (GA)

GA [69] is a stochastic, biological evolution technique that is routinely used to solve the nonlinear equations. It primarily relies on the initial random population generation, which is then improved using selection, crossover and mutation. These steps are repeated through generations until the stopping condition is reached: usually a satisfactory good fitness value or a predefined maximum number of generations. The variables to be solved are collected in the form of vectors called chromosomes. These chromosomes undergo the processes of crossover, mutation and selection to choose the fittest of all the chromosomes. GA mostly follows the Roulette wheel selection process in which the fittest chromosome occupies larger area and hence is the more probable candidate to get selected. The general flow chart of GA is shown in Fig. 5.

An initial HEPWM work using GA is focused on removing the first three odd harmonics of a single phase inverter to improve the power factor of its unipolar output voltage [37]. Since GA is an optimizer, the equations need to be converted to a minimization problem, and then assessed using certain fitness function. In [70] the Real Coded Genetic Algorithm (RCGA) along with the Direct Search (DS) method is employed to solve the HEPWM problem for inverter with bipolar output. The RCGA is a modified version of GA, in which binary genes are replaced by the real

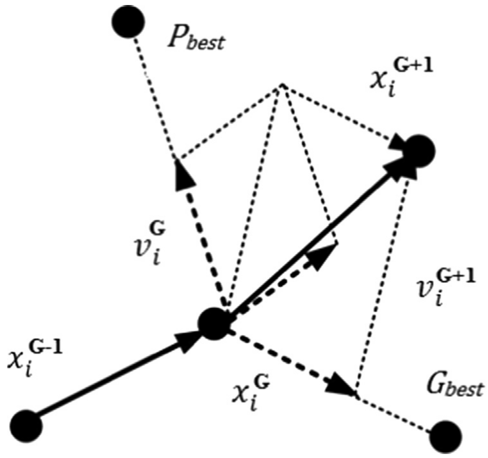

Fig. 6. Particles movement in PSO.

Step 1
Setting values of the control parameters of PSO:
population size N_P, inertia w, learning factors c_1 *and* c_2
Step 2: Initialization
Set the generation number $G = 0$
and randomly initialize a population of N_P individuals with
$X_{i,G} = [X_{1,i,G}, X_{2,i,G}, X_{3,i,G}, \ldots.., X_{D,i,G}]$ and each individual
uniformly distributed in the range $[X_L, X_H]$ as:
$X_{j,1,0} = X_L + rand[0,1](X_H - X_L)$ where
$X_L = [X_{1,L}, X_{2,L}, \ldots, X_{D,L}]$ and
$X_H = [X_{1,H}, X_{2,H}, \ldots, X_{D,H}]$ with $i = [1, 2, \ldots., N_P]$.
Initialize position, P_X, and velocities, V_X, of the particles:
Step 3
WHILE the stopping criterion is not satisfied
DO
FOR i = 1 to N_P
Step 3.1: Calculate P_{best} and G_{best}
Evaluate the fitness of particles
IF $F(X_{i,G+1}) < F(X_{i,G})$ THEN $P_{best,i,G} = X_{i,G+1}$
ELSE $P_{best,i,G} = X_{i,G}$
ENDIF
$G_{best,G} = \min(P_{best,i,G})$
Step 4: Update Position and Velocity
Calculate the velocities and positions of particles in the following way:
$V_{X,i,G+1} = w^*P_{X,i,G} + c_1{}^*r_1{}^*(P_{best,i,G} - P_{X,i,G})$
$\quad + c_2{}^*r_2(G_{best,G} - P_{X,i,G})$
$P_{X,i,G+1} = P_{X,i,G} + V_{X,i,G+1}$
END FOR
Step 5: Increase the Generation Count
$G = G + 1$
END WHILE

Fig. 7. The general pseudocode of PSO.

numbers to reduce the convergence time and to improve the accuracy of the solution [71]. First, the global searching ability of RCGA is activated to find the solution with minimum weighted THD (WTHD)[1]; then it is fine-tuned by the local searching ability of DS. The selection is done according to the Roulette wheel method. Once RCGA passes the fitness test, the solution is handed over to DS as its initial guess. In another work [72], a similar approach using RCGA and DS (as described above) is carried out for the single and three phase electrical utility high power inverters.

In [48] a hybrid algorithm that combines the RCGA and the Pattern Search (PS) for ac–ac converters is proposed. The RCGA is used as a priority optimization tool while PS is used to make the solution precise in every evolution. The objective of the paper is to improve the convergence rate by replacing the ordinary mutation process by the breeder GA mutation, as proposed in [73]. Moreover, elitist strategy is introduced to retain the best individuals for the next generation. In [46], a hybrid approach comprising of GA and NR is used to improve the power quality of the single phase grid connected systems. First the GA is employed to estimate the best possible global minimum locations; then using these solutions as its initial guesses, the NR algorithm is used to solve the HEPWM equations.

For the application of HEPWM in MVSI, the RCGA-DS (as described in [70]) is applied to a three level neutral point clamped (NPC) inverter [74]. Ideally, HEPWM waveform has the ability to remove any neutral point current due to its quarter and half wave symmetries. However, because of the variation in the load current and operating conditions, a small amount of neutral point current circulates, which decreases the efficiency and performance of the inverter system. To resolve this issue, the proposed method is designed to operate in two steps; in the first step, a specific amount of harmonics are removed by the ordinary HEPWM method, while in the second step a small change in switching angles is done to minimize the neutral point current. The change in angles is calculated according to the charging and discharging timings of the input capacitors.

A new class of MVSI with a comparatively less components for medium power applications is introduced in [67]. It only requires a set of two auxiliary switches and a normal H-bridge configuration to produce a five level output waveform. Furthermore, it can be extended to any number of levels by increasing the auxiliary switches sets. These auxiliary switches are used to generate the type-*a* output waveform and they operate by doubling the switching frequency of H-bridge switches. In this work, the HEPWM angles are solved using GA. As the angle trajectories contain multiple solutions for a single value of modulation index (M), the solution that yields the best THD is picked.

In [75] the GA and PSO are used to compute the angles for the cascaded MVSI type-*a* output waveform. To achieve high quality sinusoidal waveform, 41 and 20 levels MVSIs are proposed. This scheme requires twenty and ten switching angles to be solved, respectively. Furthermore, twenty and ten voltage variables are also introduced to improve the regulation of the output voltage of the respective inverters. Once the values of these variables are found, they are tuned to obtain the possible best value of THD. In another similar work [33], the HEPWM computation for seven level three phase diode clamped MVSI is implemented. In the first stage, the RCGA and PSO are used separately to solve this problem. In the next step NR is used to refine the solution by using the best solution provided by RCGA or PSO as an initial guess.

In [76] the objective functions of the MVSI (Eq. (8)) for the type-*b* HEPWM case are derived and solved for both the equal and unequal input voltage sources. The paper demonstrates the superiority of the type-*b* output over type-*a*. Moreover, it also makes use of the maximum switching frequency of the switches. In order to verify the viability of the method, a single phase as well as a three phase five and seven level inverters are considered. The HEPWM problem is solved by the hybrid GA method of [70].

[1] Weighted THD is defined as $\mathrm{WTHD} = \sqrt{\sum_{i=2}^{k}(w_iV_i)^2}/V_1$ where w_i is the weighting constant while V_i and V_1 are the rms values of ith and fundamental component of the output voltage. In order to get the minimum value of WTHD, w_i is chosen as a real number between the interval 0 and 1. It can also be chosen as $1/i$, where index i represents the harmonic under consideration. The value of w_i is chosen in such a way that more emphasis can be made on the lower order harmonics.

For convenience, Table 1 provides the summary of the HEPWM work based on GA. It also summarizes the work carried out in every reference.

3.2. Evolutionary programming (EP)

EP is a probabilistic optimization method where the mutation is carried out through Gaussian random variable $N(0, \sigma_i^2)$ as follows:

$$P_i' = P_i + N(0, \sigma_i^2) \quad \text{for} \quad i = 1, 2, ..., N_p \tag{9}$$

where N_p, P_i and P_i' are population, the current and new population vectors, respectively. The variable σ_i is the standard deviation, which is given as

$$\sigma_i = \beta f_i / f_{min}(P_{i-\ max} - P_{i-\ min}) \tag{10}$$

In Eq. (10), β is the scaling factor, f_i is the fitness of ith vector and f_{min} is the minimum fitness of the whole population. Moreover, $P_{i\text{-}max}$ and $P_{i\text{-}min}$ represent maximum and minimum limits of the population vectors, respectively. The selection process follows the Stochastic tournament method, in which the parents and offsprings are compared with the randomly generated vectors in a series of N_t tournaments. A score is awarded to them, according to their accuracy. At the last step, all vectors are arranged in a descending order of their scores with the first N_p vectors picked as target vectors for the next generation.

In [27] the HEPWM problem for three phase inverter with unipolar output is solved through GA and EP. The objective of the paper is to improve the performance of induction motor drives by mitigating certain number of harmonics from the output voltage of the inverter. First, GA is performed with the Roulette wheel selection method. Moreover, in order to get the better converging behavior of GA, the elitist is employed. Once the problem is solved through GA, it is solved again by using EP.

3.3. Particle Swarm Optimization (PSO)

PSO [77] is based on the behavior of swarms (in the PSO context are called particles). Each particle is influenced by its own best position (P_{best}) and the best known positions in the search-space. The latter is guided by the neighborhoods (G_{best}) best position. An inertia weight controls the velocity of the motion of the particles. The general idea of particles movement in PSO is illustrated by Fig. 6.

Based on Fig. 6, the individual particle position is defined by

$$x_i^{G+1} = x_i^G + v_i^{G+1} \tag{11}$$

where, v_i represents the velocity component and is calculated by

$$v_i^{G+1} = wv_i^G + c_1 r_1 (P_{besti} - x_i^G) + c_2 r_2 (G_{best} - x_i^G) \tag{12}$$

In Eq. (12), w is the inertia weight; c_1 and c_2 are the acceleration constants, while P_{besti} and G_{best} are the personal and global best positions, respectively. To start the optimization process, a solution vector of the HEPWM angles are initialized, which are presented by x_i in Eq. (11). In the next iteration, all particles are heading towards their local best position P_{best}. Among these particles, one of them is the global best G_{best}. It gives the best fitness value. After calculating the velocity, which serves as a perturbation to the angles, a new position of the duty cycle is found. Through successive iteration all particles move towards global best position. As the particles approach the correct values of the angles, they get closer to the G_{best} position. Correspondingly, the P_{best} and G_{best} factor in velocity term moves towards zero, which indicates that the solution is found. The general pseudocode of PSO is given in Fig. 7.

Step 1
Setting values of the control parameters of PSO:
population size N_P, inertia w, learning factors c_1 and c_2
Step 2: Initialization
Set the generation number $G=0$
and randomly initialize a population of N_P individuals with
$X_{i,G}=[X_{1,i,G}, X_{2,i,G}, X_{3,i,G},\ldots, X_{D,i,G}]$ and each individual
uniformly distributed in the range [X_L, X_H]
as:$X_{j,I,0} = X_L + r$ and $[0,1](X_H - X_L)$ where
$X_L = [X_{1,L}, X_{2,L}, \ldots, X_{D,L}]$ and
$X_H = [X_{1,H}, X_{2,H}, \ldots, X_{D,H}]$ with $i = [1, 2, \ldots, N_P]$.

Initialize position, P_X, and velocities, V_X, of the particles:
Step 3
WHILE the stopping criterion is not satisfied
DO
FOR $i=1$ to N_P
Step 3.1:

Table 2
Summary of the PSO related work in HEPWM.

Authors	Reference	Objectives of the work	Remarks
R.N. Ray, D. Chatterjee, and S.K. Goswami	[30]	Control of THD and to remove discontinuities in the HEPWM solution	A THD based PSO is used to obtain the angles with minimum THD of the VSI. Discontinuity of the solution angles is also removed by using the same method
H. Lou, et al.	[47]	Power factor control	Combination of PSO and NR is used to improve the power factor and harmonics profile of the ac-dc converter
S. Barkat, E.M. Berkouk, and M.S. Boucherit	[38]	Harmonics removal and voltage regulation in MVSI	PSO is used to regulate the output voltage and to improve the harmonics profile of MVSI systems
R.N. Ray, D. Chatterjee, and S. K. Goswami	[78]	Control of THD and the discontinuity in the solution for MVSI	Method of [30] is used to extend the work for MVSI
C.R.S. Reinoso, et al.	[79]	Efficiency improvement of the PV system	PSO is applied to improve the harmonics profile of MVSI. Emphasis is on the efficiency of PV systems
A.K. Al-Othmanand T. H.Abdelhamid	[81]	Harmonics control for the MVSI having unequal DC voltage sources	Unequal input DC sources are used to solve the HEPWM problem for MVSI. PSO has been applied to control the THD and the linearity of the switching angle trajectories
H. Taghizadeh and M. T. Hagh	[82]	Harmonics control for the cascaded MVSI having unequal input DC voltage sources	Same procedure of [81] is used for cascaded MVSI
M.T. Hagh, H. Taghizadeh, and K. Razi	[84]	Harmonics control with good convergence rate for MVSI	Modified version of SPSO is used to solve the HEPWM problem for MVSI. Modification is done to improve the convergence behavior of SPSO for HEPWM

Calculate P_{best} and G_{best}
Evaluate the fitness of particles
IF $F(X_{i,G+1}) < F(X_{i,G})$ THEN $P_{best,i,G} = X_{i,G+1}$
ELSE $P_{best,i,G} = X_{i,G}$
ENDIF
$G_{best,G} = \min(P_{best,i,G})$
Step 4: Update Position and Velocity
Calculate the velocities and positions of particles in the following way:
$V_{X,i,G+1} = wP_{X,i,G} + c_1 r_1 (P_{best,i,G} - P_{X,i,G}) + c_2 r_2 (G_{best,G} - P_{X,i,G})$

$P_{X,i,G+1} = P_{X,i,G} + V_{X,i,G+1}$

END FOR
Step 5: Increase the Generation Count
$G = G+1$
END WHILE

A THD-based PSO is introduced in [30] to minimize the THD of the VSI with bipolar output. Instead of Eq. (5), Eq. (1) is used as an objective function; hence the term THD-based PSO. The change of objective function has alleviated the need of solving the difficult nonlinear transcendental equations as well as ensuring an improved harmonics spectra of the VSI. A hybrid PSO (HPSO) proposed in [47] combines the PSO (as in [30]) and the NR methods. Its objective is to increase the efficiency of the inverter with unipolar output voltage by controlling the power factor of the load. First, the PSO is used to find the possible best solution, which is then handed over to NR as its initial guess to find the exact solution.

Due to its excellent searching capability, PSO is mainly focused to solve the more difficult HEPWM problem for multilevel inverters. In [78], PSO is utilized to obtain the switching angles for the cascaded MVSI. It is also used to ensure the discontinuities in the switching angle trajectories for the type-*a* case are mitigated in the seven and eleven level in the cascaded inverters, respectively. Moreover, the work is extended to the type-*b* HEPWM problem by finding additional four and six switching angles, thus improving the harmonic spectra greatly. Similar approach is adopted in [79], which demonstrates the application of the cascaded MVSI and HEPWM in a PV systems. In another work [38], PSO is used to compute the HEPWM angles of the type-*a* waveform for the seven and eleven level diode clamped MVSI. It is worth noting that in most papers related to MVSI, the dc inputs are assumed to be of equal magnitudes. However, in practice, particularly for RE applications, the sources may exhibit unequal magnitudes [80]. Thus, the results obtained for the case of equal magnitude sources are not applicable. In [81,82], type-*a* HEPWM waveform is solved by PSO for the cascaded five, seven and nine level inverters with unequal dc sources.

A modified version, called the species-based PSO (SPSO) [83] is used to solve the type-*b* HEPWM problem in [84]. SPSO utilizes the l_{best} scheme instead of the P_{best}. To obtain the l_{best} value, the particles are first arranged according to their increasing fitness. They are divided into n_s species, with the best solution being taken as the leader particle. This is termed as *species seed*. Moreover, all particles having the same Euclidean distance (r_s) with the species seed are grouped as one species. Then,the redundant particles (i.e the paticles having the same fitness value) are replaced by the new particles. The latter are randomly generated. In [84] an adaptive SPSO for HEPWM is proposed. Instead of keeping r_s and n_s constant throughout the process, they are varied adaptively to guide the SPSO towards the global minimum. The objective is to enhance the convergence of the SPSO by converting it to an adaptive algorithm. Table 2 summarizes the application of PSO for HEPWM.

3.4. Differential Evolution (DE)

DE is a stochastic, optimizer based evolutionary algorithm. Unlike GA, which relies on crossover, DE primarily utilizes the mutation operation (i.e. the difference vector) as a search and selection mechanism to direct the search towards the prospective regions in the search space. Fig. 8 depicts the basic concept of DE. The population is defined as X_i (j), which is randomly initialized

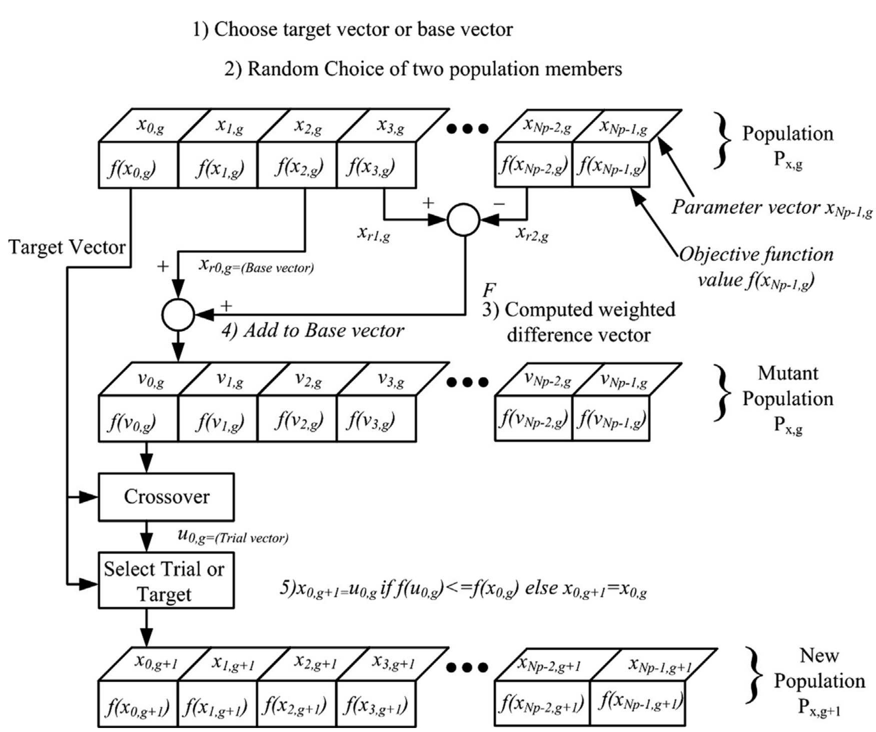

Fig. 8. Basic flow of DE algorithm [85].

within the initial parameter bounds (High (H) and Low (L)), i.e.

$$X_i(j) = X_{iL} + \mathrm{rand}(0,1)[X_{iH} - X_{iL}] \tag{13}$$

In each generation, the individuals of the current population become target vectors. For each target vector, the mutation operation produces a mutant vector, by adding the weighted difference between two randomly chosen vectors to a third vector, as presented below:

$$X_{i,G+1} = X_{r1,G} + F(X_{r2,G} - X_{r3,G}) \tag{14}$$

where F is the mutation rate constant. The crossover (controlled by the crossover rate, CR) generates a new vector, called the trial vector $U_{i,G}$ (Eq. (15)). It is achieved by mixing the parameters of the mutant vector $V_{i,G}$ with those of the target vector $X_{i,G}$. Every trial vector is then assessed by the fitness function. If the trial vector has a better fitness value than the target vector, the trial vector replaces the target vector in the next generation. The process is repeated through the generations until the stopping condition is reached.

$$U_{j,i,G+1} = \begin{cases} V_{j,i,G+1}, \textit{if } j = l \text{ or } r \text{ and} \le CR \\ X_{j,i,G+1}, \text{otherwise} \end{cases} \quad i = 1,2,\ldots,N_P \tag{15}$$

In [29,86] DE is used to solve the HEPWM for a three-phase VSI with bipolar output voltage. In another work [87] a modified form of DE is used to improve the performance of a three phase induction motor systems by improving the harmonics behavior of the inverter. To obtain a maximum number of possible solutions the neighboring area of target vector $X_{i,G}$ of pre-specified radius R is searched inside the whole search space. Mutation is carried out according to the following equation:

$$V_{i,G} = X_{i,G} + F(X_{n\_best,G} - X_{i,G}) + F(X_{r_1{}^i,G} - X_{r_2^i,G}) \tag{16}$$

where r_1 and r_2 are random indices inside the predefined Euclidean distance R of $X_{i,G}$. After each iterations, the sorting of individuals is done according to the ascending order of their Euclidean distance from the origin. This is done to expedite the convergence process. In another work [88], DE is used to find out the multiple solution sets of switching angles for a bipolar VSI. However, the lowest THD valued solution is taken as the required solution. Various numbers of harmonics are removed to show the credibility of DE.

From the work carried out in [86–88], it is discovered that DE exhibits several features that could be important for HEPWM work: (1) it has rapid convergence and (2) it uses fewer control parameters. Despite the good efficiency of the algorithm, DE is yet to be applied to MVSI.

3.5. Minimization technique

A new minimization technique is introduced to solve the bipolar HEPWM problem in [89]. It consists of three main phases. The first phase utilizes the GA or Nelder Mead Simplex Algorithm which is followed by the Random search method in the second phase. The RS is used to solve the angles for one value of M, say $M = 0.1$. Once the switching angles for this value are obtained, remaining values (for the whole range of M) are found by utilizing the switching angles of the neighboring M as an initial guess for NR. As the angle trajectories of the HEPWM method contains multiple solution sets, the Harmonic Distortion Factor (HDF)[2] criteria is used to decide the best solution. In [90] similar minimization technique is used to solve the HEPWM problem for unipolar output waveform of the single phase inverter.

In [51] the application of the minimization method introduced in [89] is extended to the type-b HEPWM problem for MVSI. A seven level cascaded inverter with equal input dc voltage sources is used as a test case. The objective of the work is to mitigate the discontinuities in the solution within the range of $1.5 < M < 3$. For $M < 1.5$, solutions using the five, three or two level inverters are suggested. Furthermore, various switching combinations are tried for each level.

3.6. Ant colony systems (ACS)

ACS [91] mimics the food searching behavior of ants. It is unique compared to other SC methods in a sense that all the ants are finally gathered at the global optimum point, while in other SC, only a few individuals gather at that point [62]. In the path of their food search, ants use to deposit a special substance called '*pheromone*'. The higher the *pheromone content*, the greater is the probability of finding food along that path. This path not only helps the ants to trace their way back to home but also acts as a gathering tool for other ants at the point of food supply. The location visited by ants as well as its *pheromone content* is stored in the *Tabu* list. The pheromone content at any location is found as

$$\tau_j(t) = (1-\rho)\tau_j(t-1) + \frac{1}{F_j(\alpha)+1} \tag{17}$$

where $\tau_j(t)$ and $\tau_j(t-1)$ are the pheromone contents at the present and previous stages of jth location. Variable ρ is the evaporation constant, which is randomly chosen between 0 and 1; $F_j(\alpha)$ is the fitness function value at the jth location.

In [62], the original ACS algorithm is modified by adding a variable named as *step length of the ant movement*. It tells the ants the allowable step length to move to the next location of their search. Ants move according to the values of the pheromone content and the movement probability, p_j. The latter is defined as

$$p_j = \frac{\tau_j^m}{\sum_1^n \tau_j} \tag{18}$$

where m is the order of pheromone. If the value of movement probability 'p_j' is greater than a threshold probability 'p_t' (randomly chosen real valued number between 0 and 1), it indicates that the ant is in the promising region of the global minima; otherwise it is located in the less favorable region. In [62], the ACS is applied to remove the harmonics from the unipolar output voltage of three phase inverter. The objective of the paper is to improve the convergence of the HEPWM algorithm.

3.7. Clonal search algorithm (CSA)

CSA [92] follows the Clonal Selection Theory, in which the better cloned antibodies survive to act against antigen invaders. In CSA, the antibodies are the target vectors and are generated randomly. As N_P antibodies are generated, so are their clones. Instead of mutating the antibodies, the mutation is carried out on their clones to save the original vectors from any disturbance. After the clonal mutation, the selection is done in which the fittest antibodies among the original and the mutated clone antibodies will survive. Since CSA searches the whole search space, it generates a large number of infeasible solutions. Thus, to assist the CSA in finding the global minimum, the *Infeasibility Degree Random Disturbance Selection* (IFDD) method is introduced in [68]. New solutions are treated as improved solutions if the value of the IFDD is less than its critical value (ϕ_{crit}), otherwise they are discarded and replaced by the most feasible solutions. In [68] the

[2] The Harmonic Distortion Factor (HDF) criteria is defined as follows:

$$\mathrm{HDF} = \frac{\sqrt{V_a^2 + V_b^2}}{V_1}$$

where V_1 is the magnitude of fundamental voltage component, while V_a and V_b are the magnitude of the first two un-eliminated voltage components. The HDF is normally cited in per unit (p.u.).

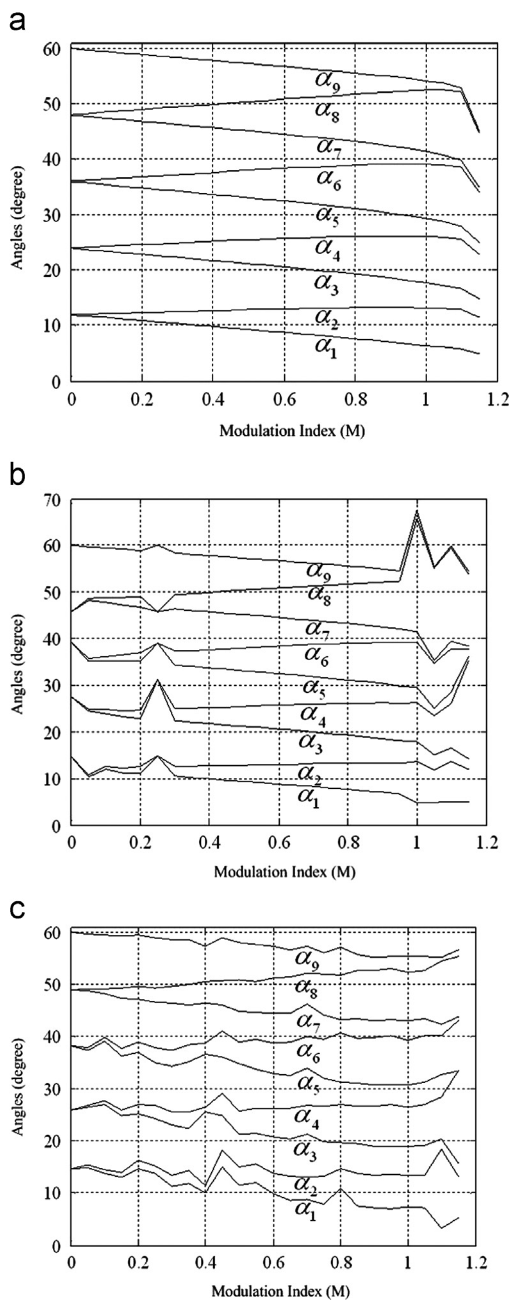

Fig. 9. Trajectory of angles for seven eliminated harmonics (a) DE (b) PSO and (c) GA.

HEPWM problem for unipolar three phase VSI is solved using CSA. The objective of the work is to remove the harmonics from the output voltage of the variable frequency motor drive systems by considering the THD minimization as the objective function.

3.8. Bee algorithm (BA)

Bee algorithm [93] follows the foraging behavior of honeybees. The bee itself can be one of the three kinds, namely: employed bees, onlooker bees and the scout bees. Employed bees are equal to the number of randomly initialized food places (variables containing vectors) and are half of the bee colony; while remaining half is comprised of the onlooker bees. The BA algorithm consists of three phases. In the first phase, each employed bee is sent towards a single food place to carry out the searching process. After completing their task, they come back and handover the information of the best visited food places to the onlooker bees. In the second phase, onlooker bees start their search by gathering at the best food locations visited by the employed bees. More onlooker bees are gathered at the food points which contain more nectar. During their search process, both the employed bees and the onlooker bees try to modify and find the best solution place; which is saved as a new food place only if it has better fitness value. Once the onlooker bees have done their work; unimproved food places are replaced by the new randomly initialized food places. In the last phase of BA search, the employed bees are sent as the scout bees to find out the best food place; which is then memorized by them. The process continues till the ending criterion is met.

In [94] Bee Algorithm (BA) is used to solve the type-*a* HEPWM problem for 7 level cascaded MVSI, with special emphasis on the removal of lower harmonics. The credibility of BA is shown by comparing the fitness value of its solutions with different predefined values of objective function through Cumulative Distribution Function (CDF).[3]

3.9. Bacterial foraging algorithm (BFA)

BFA [95] is based on the behavior of *Escherichia Coli* bacteria. It consists of four major steps, namely chemotaxis, swarming, reproduction and elimination dispersal. Chemotaxis controls the movement (*tumbling*) of bacterium according to the following equation

$$\alpha^i(o+1,u,v)=\alpha^i(o,u,v)+C(i)\frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}} \tag{19}$$

where o, u, v represent the step numbers of chemotaxis, reproduction and elimination dispersal processes. Variable $C(i)$ is the step size of chemotaxis while Δ represents a random direction vector of range $[-1, 1]$. Bacterium which finds the best solution utilizes the process of swarming to gather maximum bacteria at that point. Swarming is followed by the reproduction and elimination dispersal, in which weak bacteria (having bad fitness value) are replaced by the strong bacteria (having good fitness value). The latter are then dispersed to find the optimum solution.

In HEPWM literature, the type-*a* MVSI for thirteen and seventeen level has been solved by BFA [96]. In this work, more emphasis is put on the removal of lower order harmonics. Moreover, the credibility of BFA is shown by comparing the fitness value of its solutions with different predefined values of objective function through Cumulative Distribution Function (CDF).

4. Evaluations of techniques and discussions

4.1. Evaluation of three prominent methods

It is rather difficult to directly compare all the methods described above based on the data or results available from the literature alone. This is because the experiments carried out in each paper differ in terms of number of angles to be eliminated, its objective function, selection of SC control parameters, levels of output voltage (for MVSI), number of phases, etc. Furthermore, the criteria for evaluation, if any, are not consistent. It appears that each method adopts different performance index to claim its superiority over others, despite the absence of clear and fair justifications. Consequently the true performance of the said SC

[3] CDF is defined as $\mathrm{CDF}(y)=Probability(Y<y)$; in other words CDF gives the probability of finding a random variable Y (real valued with a given probability distribution), at a value less than or equal to x.

Table 3
The Fitness values and number of iterations to eliminate eight harmonic (with fundamental control) using DE, PSO and GA (averaged over 20 runs).

Modulation Index, M	DE		PSO		GA	
	Fitness value	Iterations	Fitness value	Iterations	Fitness value	Iterations
0.01	8.5×10^{-6}	3050	9.0×10^{-3}	9000	7.7×10^{-3}	9000
0.11	9.3×10^{-6}	0964	1.1×10^{-1}	9000	8.7×10^{-2}	9000
0.21	9.2×10^{-6}	0970	8.5×10^{-2}	9000	1.4×10^{-1}	9000
0.31	8.1×10^{-6}	0069	9.9×10^{-6}	1347	8.1×10^{-2}	9000
0.41	9.1×10^{-6}	0366	8.8×10^{-6}	1852	3.5×10^{-1}	9000
0.51	7.8×10^{-6}	0070	6.5×10^{-6}	1225	2.2×10^{-1}	9000
0.61	6.9×10^{-6}	0365	9.2×10^{-6}	1235	1.7×10^{-1}	9000
0.71	6.8×10^{-6}	0663	9.8×10^{-6}	1972	3.8×10^{-1}	9000
0.81	6.2×10^{-6}	0376	9.1×10^{-6}	1877	3.7×10^{-1}	9000
0.91	9.7×10^{-6}	0065	9.2×10^{-6}	2534	9.4×10^{-2}	9000
1.01	8.2×10^{-6}	0071	9.9×10^{-6}	3213	1.9×10^{-1}	9000
1.11	9.6×10^{-6}	0064	1.7×10^{-4}	9000	6.4×10^{-1}	9000
1.16	8.9×10^{-6}	5734	1.2×10^{-2}	9000	3.3×10^{-1}	9000

methods could not be conclusively determined. In view of these facts, this section attempts to conduct a comprehensive evaluation of three selective SC methods, i.e. GA, PSO and DE. The GA and PSO are selected due to their popularity (as the most widely used algorithms for this application), while DE is considered based on its interesting features that are potentially valuable for HEPWM. Other methods, i.e. CSA, BA and BFA are not considered for evaluation, because of their lesser importance. For the minimization technique, the algorithm is also strongly influenced by GA and NR [89]; hence is also left out.

4.2. Methods of comparison

To evaluate their effectiveness, all the three chosen methods are critically evaluated based on: (1) the accuracy of solution, (2) its computational speed and (3) the rate of convergence. A single phase VSI with bipolar output waveform is used as the test case. To ensure a fair comparison, the basic parameters, i.e. population size, maximum generation number and search ranges are made consistent. The population size (N_P), is chosen to be 10 k, where, k is the number of switching angles to be calculated. In this particular case, $k=9$; this implies that eight harmonics will be eliminated, along with the ability to control the fundamental component amplitude.

For GA, a crossover rate of value 0.8 and the mutation rate of value 0.2 are used. Furthermore, a GA function "*ga*" in MATLAB is utilized. For PSO implementation, the following control variables are used: $c_1=1.6$, $c_2=1.2$ and $w=0.5$ [97]. The parameters of GA and PSO are selected based on the common values given in the literature or by means of a trial and error process to achieve the best solution set. For DE, the mutation factor (F) is set at 0.8. There is no strict rule on the choice of F but in most cases, $F>0.4$ [98]. The crossover rate (CR) is chosen to be 1.0. Large value of CR intensifies the diversity of population, thus improving the convergence speed. Moreover, a high value of CR is desirable as the parameters in the model are highly correlated [99,100]. The DE/best/1/bin strategy is used for the DE [101]. The generation size for each algorithm is set to 300. The, fitness value, i.e. the objective function to minimize each harmonic is defined as

$$F(\alpha)=|\varepsilon_1|+|\varepsilon_2|+|\varepsilon_3|+\ldots+|\varepsilon_k| \tag{20}$$

where ε_κ indicates the allowable error for each harmonic, which is set to be less or equal to 1×10^{-5}. Two types of stopping conditions are used, whichever comes first: (1) when the algorithm attains a specified $F(\alpha)$ value, or (2) when algorithm reaches to a maximum number of iteration, G_{max}, which is set to 9000.

4.3. Results

4.3.1. HEPWM angles trajectories

Fig. 9(a)–(c) shows the trajectories of the HEPWM switching angles (α_1–α_9) to eliminate eight harmonics plus the ability to control the fundamental component (by changing the modulation index, M). The nine angles are computed with the variation of, M, stepped at 0.05 per computation. From Fig. 9(a), it can be seen that DE provides solutions with almost linear trajectories for all values of M until the over-modulation region ($M>1.0$). This can be observed by the formation of linear slopes of the trajectories, i.e. $d\alpha/dM$ up to the over-modulation range. The main advantage of having linear trajectories is the possibility to derive an approximate solution for the HEPWM angles, as demonstrated by [102]. On the other hand, for PSO and GA their trajectories are very irregular, with inconsistent values of $d\alpha/dM$. Furthermore, particularly for PSO, it can be seen that at low values of M (<0.15), the adjacent angles (for example α_1 and α_2) tend to overlap each other, i.e. they have almost zero angular separation. Such condition is not desirable because practically, the pulse cannot be created as the power transistor of the inverter requires finite time to switch on and off. This drawback is more significant because the HEPWM switching is typically used in high power converter with larger transistor rise and fall times.

4.3.2. Accuracy

The detailed evaluation of each computational method can be extracted from Table 3. The fitness values and the iteration time are the average taken over 20 runs. With regard to the fitness value, DE consistently has very low values of $F(\alpha)$ for the entire range of M. All the values are in the 10^{-6} range; this fact is an indication of its excellent accuracy. The accuracy of PSO is in the same order with DE in the mid range of modulation index ($0.3<M<1.0$). However, at both extremes, i.e. for $M=0.01$, 0.11, 0.21, 1.11 and 1.16, its accuracy deteriorates drastically by several orders of magnitude (10^{-1}–10^{-4}). Among the three, it appears that the accuracy of GA is the most inferior. The best achievable value for $F(\alpha)$ is in the 10^{-4} region.

4.3.3. Convergence rate

The number of iterations required to achieve the designated accuracy determines the convergence rate. From Table 3, it can be clearly seen that DE converges very quickly to the specified fitness value, i.e. within less than 100 iterations for most of M values. In the mid-range values of M, the PSO convergence is approximately one order of magnitude higher than DE. However, at the extreme

ends, the algorithm could not converge to the required $F(\alpha)$ even when the iterations reached the stopping condition (G_{max}=9000). In the case of GA, it never achieves the specified value of $F(\alpha)$ and always terminates at the stopping condition. The GA algorithm spends most of its time competing between different peaks, rather than improving the solution along a single peak (global optima) at which the optimal point is located [72].

4.3.4. Number of control parameters

For any SC method, fewer control parameters means simpler tuning effort and easier optimization problem. In this regard, DE requires only two parameters, i.e. F and CR. PSO requires three, namely w, c_1, and c_2. On the other hand, due to various control parameters (i.e. crossover rate, mutation factor, number of children in elite strategy and migration factor), it appears that GA is the least preferable choice among the three.

5. Conclusions

This review paper has discussed the application of the HEPWM method for the removal of harmonics from the output of the voltage source inverters. The work is expected to be useful for researchers and practitioners working on energy conversion system, in particular the renewable systems. Emphasis is given on the different soft computing (SC) techniques to solve the HEPWM computational problem. Nine SC techniques are discussed, with three, namely GA, PSO and DE being given special attention. A comprehensive evaluation is carried out and it is found that DE is the most promising due to its superior convergence and simplicity. It is envisaged that the SC methods can be effectively used to solve complex HEPWM problems of the multilevel inverter with high number of switching angles. Such capability would be very desirable, considering the growing importance of multilevel inverter for RE applications.

Acknowledgements

The authors would like to thank the Ministry of Education Malaysia, for providing the fund to carry out the research under the Exploratory Research Grant Scheme. The project was managed by the Research Management Centre, Universiti Teknologi Malaysia under Vot. Number 7823.4L005.

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